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Geomorphology, stratigraphy and Holocene history of the Rockingham-Becher Plain, South-western Australia

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Abstract

The Rockingham-Becher Plain is a large, cuspate, beachridge system in the central portion of the Cape Bouvard-Trigg Island Sector of the inner Rottnest Shelf coast. The main geomorphic components in the area are shore-parallel Pleistocene aeolianite ridges and their associated intervening depressions, and the Holocene units of basins, slopes, banks/nearshore platforms, beaches, and beachridge/dunes. The Holocene sedimentary facies have generated distinctive suites of sediments and a relatively simple stratigraphy: the facies of the basin has formed the calcareous mud of the Bridport Calcilutite, the facies of the banks, slopes, and nearshore platforms have developed the bioturbated sediment of the Becher Sand, and the facies of the beaches, beachridges, and dunes have developed the Safety Bay Sand. Most of the Holocene sequence underlying the Rockingham-Becher Plain is comprised of these stratigraphy units in simple superposition.

Radiocarbon dating of the sequences indicates that the Holocene marine record begins at 7 980 C14 yrs BP, and that beach conditions were established along the fossil shoreline at 6 645 C14 yrs BP with relative sealevel at c + 2.5 m. Since then relative sealevel has steadily dropped and sediments have accreted rapidly to develop the broad beachridge plain. Isochron configuration shows that the plain developed asymmetrically with sediment increments accumulating preferentially on the southern portion of the complex. Palaeogeographic reconstructions for the 8 000 yr record presented in 2 000 yr intervals show a complex coastal history of progressive sediment accretion, with cuspate beachridge plain progradation, bank accretion centred on two major westward prograding banks, and concomitant limestone island/reef chain erosion.

Introduction

The subject matter of this paper, the Holocene coastal plain in the Rockingham and Becher Point area, is termed herein the Rockingham-Becher Plain (Figs 1 & 2). It occurs in the central part of the Cape Bouvard-Trigg Island Sector of southwestern Australia (Searle & Semeniuk 1985). This sector is characterized by complex nearshore bathymetry of Pleistocene ridges-and-depressions and extensive accumulations of Holocene sediments that form prograded plains of beachridges and sand dunes. The Cape Bouvard-Trigg Island Sector in particular is significant in that it contains the largest accumulations of Holocene sediment in this region.

Previous work on the Rockingham-Becher Plain has dealt with: Quaternary geomorphology and stratigraphy of the Point Peron area (Fairbridge 1950); sedimentation in Warnbro Sound (Carrigy 1956); Cainozoic stratigraphy and shallow hydrology (Passmore 1970); generalized stratigraphy and geomorphology (Seddon 1972); radiocarbon dating and sealevel history (Woods & Searle 1983; Searle & Woods 1986); development of submarine banks (Searle 1984); development of soils on the plain (Woods 1984); mapping of surface geologic units (Geology Survey of WA 1985); calcrete in the coastal sands and its use in Holocene climate history (Semeniuk & Searle 1985a; Semeniuk 1986a); the definition of the Becher Sand (Semeniuk & Searle 1985b); and the description of aeolian landforms

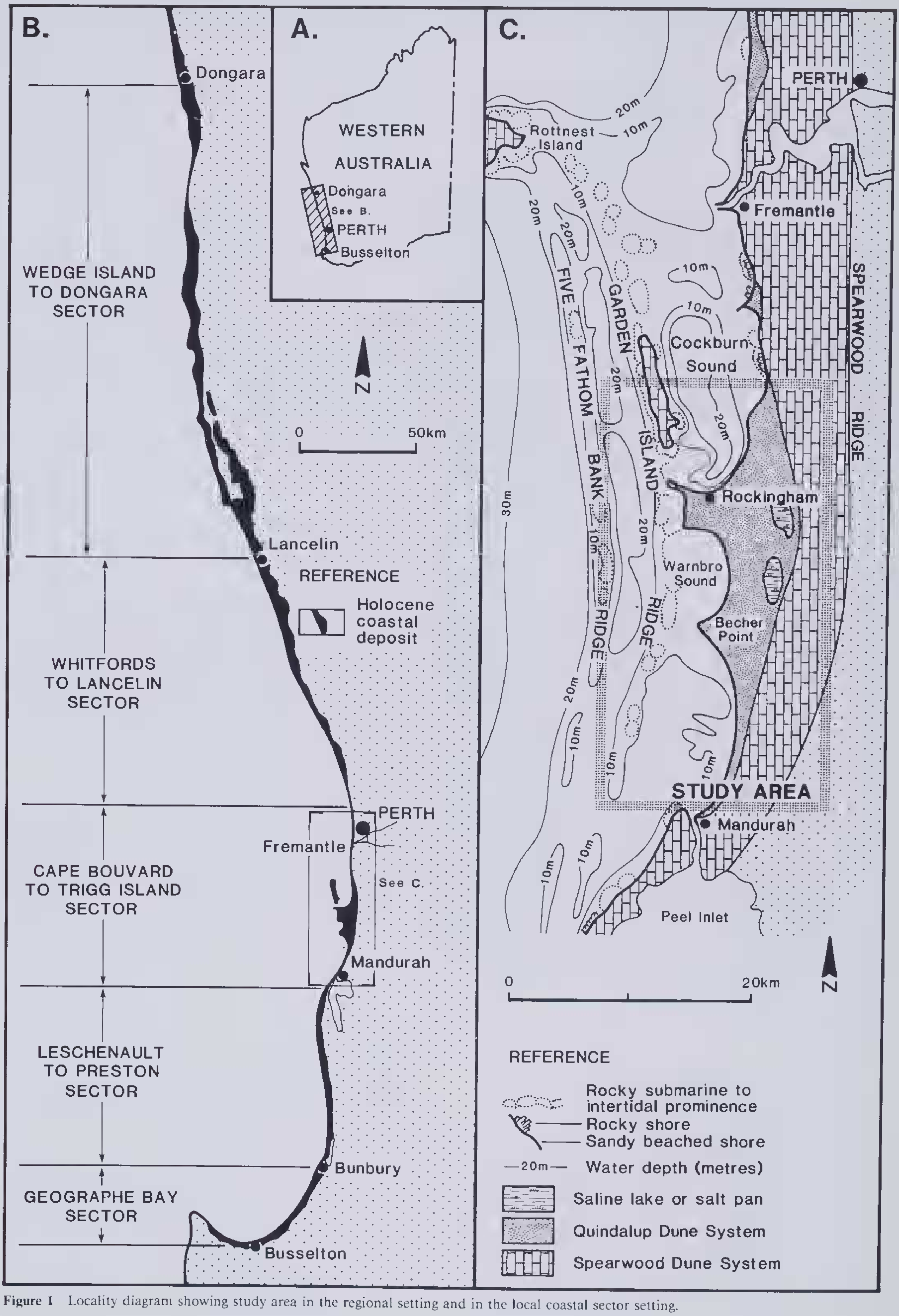

Figure 1 Locality diagram showing study area in the regional setting and in the local coastal sector setting.

Figure 2 Aerial photograph of study area showing cuspate configuration of shoreline, the chain of islands and reefs extending from Garden I through Penguin I and further south, and the prominent lineation of the beachridge patterns.

(Semeniuk et al. 1987). These works, however, do not provide the detail on, and synthesis of, the available information on the geomorphology, sedimentology, stratigraphy and age structure of the study area to the level provided herein. In particular there is still a lack of appreciation of the detailed Holocene history of the area, some of which has worldwide significance. Accordingly, this paper integrates information from the area to demonstrate how the Holocene coastal deposits formed, and to highlight its value as a natural feature of scientific significance.

Methods

Various methods were used to obtain data for this study including stratigraphic analysis, surface mapping of sediments by diver, aerial photography, granulometry and petrology of selected sediment, and radiocarbon analysis of selected shell and peat (Fig. 3).

The Holocene stratigraphy was investigated using reverse circulation coring to depths of 33 m with continuous sample recovery, percussion coring to retrieve cores to depths of 20 m, auger drilling to the water table, trenching (to 3 m below the water table using dewatering pumps) and natural exposures such as wind-eroded surfaces and cliff faces. The stratigraphy offshore was investigated with "air-lift" drilling and hand-driven cores. The "air-lift" drilling uses casing pipe and a smaller diameter compressed air powered suction pipe; penetration in excess of 10m is possible in sediments. Stratigraphic study sites were related to AHD by surveying.

The geomorphology and bathymetry of the area were documented using vertical and oblique aerial photography (at scales from 1:40 000 to 1:4 000), water penetrating aerial photography, topographic maps and bathymetric charts, and by surveying. Submarine mapping and sampling was carried out by numerous diver traverses, replicate grid sampling of substrates and by analysis of water penetrating aerial photographs. Alongshore sampling of the beach and foredune sediments also was carried out. Sediment samples were petrographically analysed using thin sections cut from resin-impregnated blocks. Selected samples were granulometrically analysed using sieves at either 0.5 or 1 phi intervals.

The age structure of the sedimentary sequence was determined by radiocarbon dating of selected shells and peat from discretely determined stratigraphic levels. This stratigraphic approach and the criteria for material selection are detailed in Woods & Searle (1983) and Searle & Woods (1986).

Regional Setting

The Rockingham-Becher Plain is located in the southern- central part of the Cape Bouvard-Trigg Island Sector. The nearshore-onshore geomorphology and bathymetry of this entire sector is dominated by a series of shore-parallel (or nearly so) submarine to emergent Pleistocene aeolianite ridges and associated depressions. These are been termed from west to east (Fig. 1; Searle 1984; Searle & Semeniuk 1985): **Five Fathom Bank Ridge; Sepia Depression; Garden Island Ridge; Warnbro-Cockburn Depression;** and **Spearwood Ridge.**

The ridges vary in relief from a few metres to in excess of 80m above the floor of adjacent depressions, and in continuity from continuous to discontinuous. The Spearwood Ridge which is part of the Spearwood Dune System (McArthur & Bettenay 1960) forms the mainland shore, and forms a topographic barrier between the inner

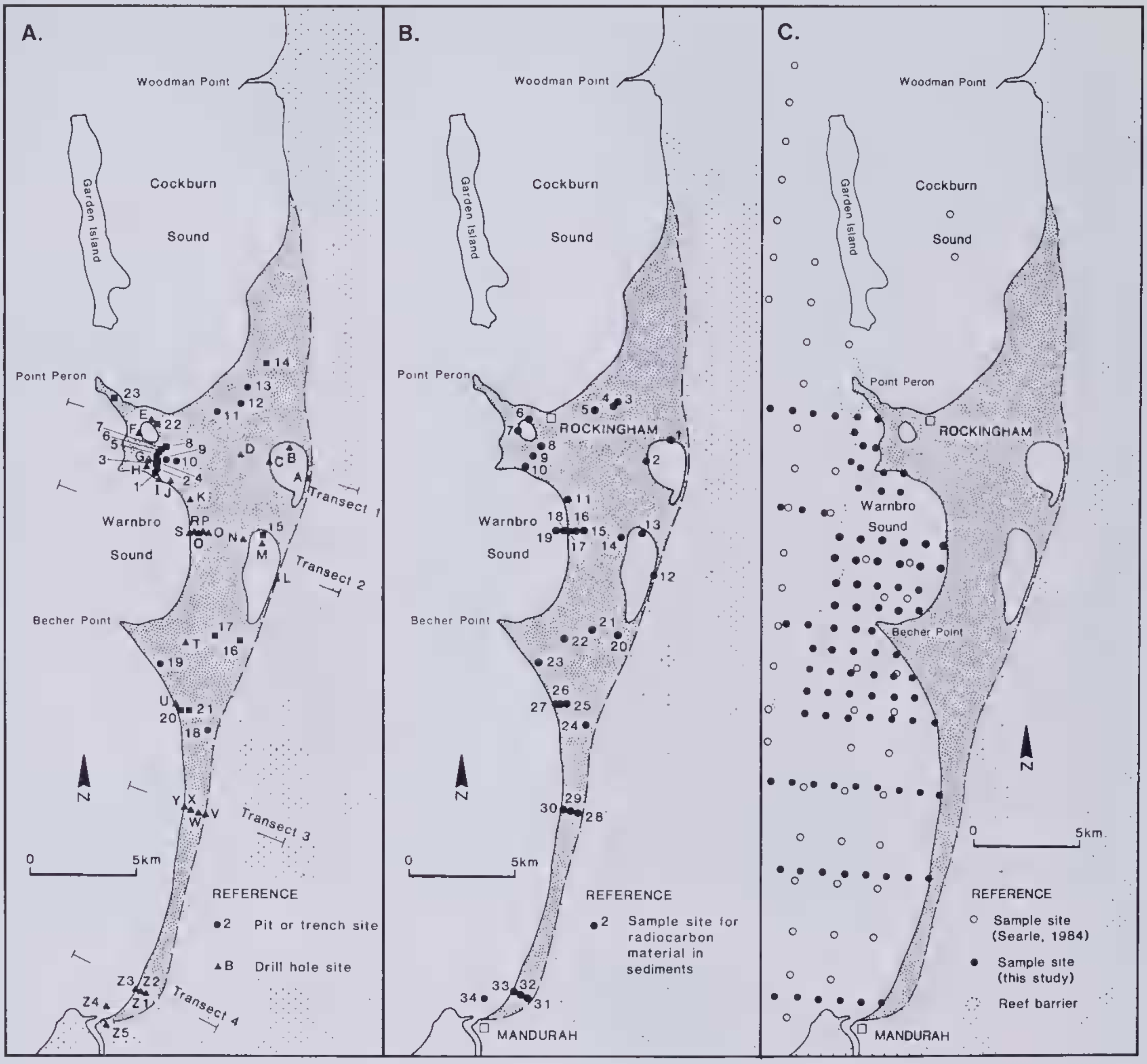

Figure 3 Sampling sites.

A Drill, trench and pit sites.
B Sample sites for radiocarbon material from beach sediment for use in Table 2 and Figure 6.
C Location of underwater sampling sites and diver traverses.

Rottnest Shelf and the low Swan Coastal Plain to the east (Fig. 1). The Garden Island Ridge is situated some 10 km offshore to the west. Holocene sediments have accumulated mostly in the depression between the Spearwood Ridge and the Garden Island Ridge.

The offshore physical oceanographic pattern along this coast is typical of the region (Steedman & Craig 1983; Searle & Semeniuk 1985). The area is wave dominated and microtidal (Hodgkin & DiLollo 1957). The inshore oceanographic pattern is specific to this sector (Searle & Semeniuk 1985). In summer the prevailing waves are oceanic swell deriving from between west and southwest, supplemented by locally-generated southwest wind waves developed by seabreezes. The complex nearshore bathymetry dampens, refracts and diffracts the swell developing complicated convergence and divergence of wave orthogonals. Locally-generated wind waves are of shorter period and wavelength, and are less modified by the bathymetry. In winter, locally-generated storm waves, which approach mainly from northwest and west, also are a significant influence on coastal processes. The dominant sand-shifting winds in the area are summer seabreezes from the southwest.

The Rockingham-Becher Plain

The natural boundaries of the Rockingham-Becher Plain are (Fig. 1): Garden Island Ridge to the west; Cockburn Sound and Garden Island to the north; the mainland Spearwood Ridge to the east; and the Peel-Harvey estuary exchange channel at Mandurah to the south. The subaerial coastal area of the Rockingham-Becher Plain essentially contains two coalesced triangular beachridge plains or cuspate forelands (Woods & Searle 1983) which are localised behind the islands, reefs and rocky prominences of the Garden Island Ridge (Fig. 1). These types of beachridge terrains are termed cuspate forelands (Bird 1976) or accretionary cusps (Semeniuk & Searle 1986a). The area also contains a variety of submarine geomorphic units that include banks, and basins.

In order to assemble the available information to a stage where the Holocene palaeogeography of the coast can be reconstructed it is necessary to describe the geomorphology, sedimentary facies, stratigraphy, age structure, and sealevel history of the Rockingham-Becher system.

Geomorphology

The various coastal geomorphic units in this area either have been developed during the Holocene as a result of sedimentary accretion, or are erosional remnants of Pleistocene landforms. In order from basement and/or deep water upwards: they are: Pleistocene ridges, basins, banks, beach zone, and beachridge and dune plain (Fig. 4).

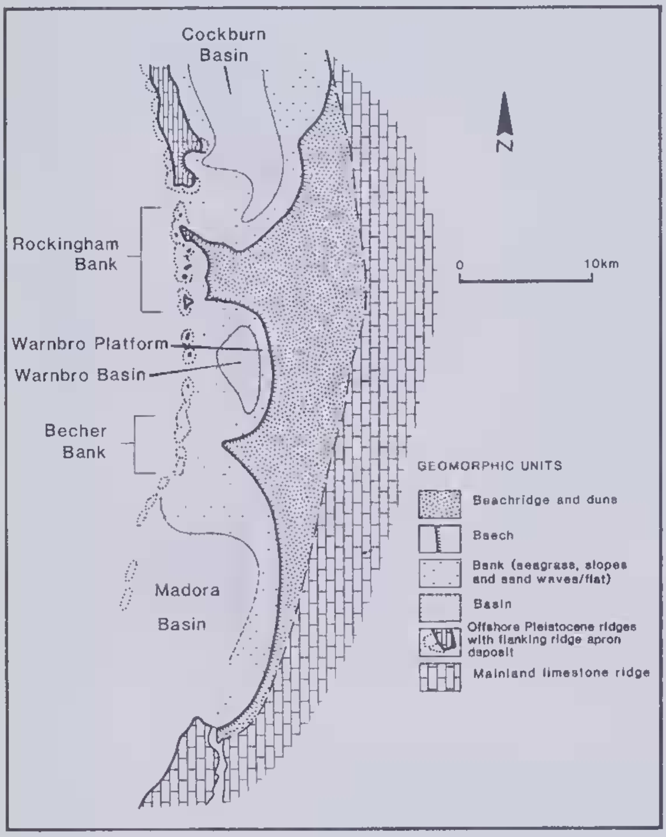

Figure 4 Geomorphic units of the study area.

Pleistocene ridges

The eroded remnants of the Pleistocene aeolianite ridges (mainly Garden Island Ridge and Spearwood Ridge) have had a major control on Holocene sedimentation and hence geomorphology. As such it is important to appreciate their influence on Holocene geomorphic history. The aeolianites of the ridges are variable in lithification, from unlithified to (most commonly) semi-lithified to locally fully indurated (calcrete capstone). This has implications for the rates of erosion of the ridges and for supply of unlithified sand to the Holocene sedimentary systems.

The Garden Island Ridge extends discontinuously north from Cape Bouvard (where it merges with the Spearwood Ridge) through to Penguin Island, Cape Peron, Garden Island and Carnac Island, before curving broadly to terminate at the western extremity of Rottnest Island (Fig. 1). The ridge rises from depths of 15 to 20 m to form a submarine to emergent chain of rocky reefs, pinnacles and islands. The islands of the Garden Island Ridge have shorelines of low (2 to 5 m high) rocky cliffs, headlands and interspersed pocket beaches (Fairbridge 1950; Semeniuk & Johnson 1985). Stacks, intertidal terraces, notches, collapsed remnants of platforms and pinnacles on the adjacent seafloor, and cliffed primary dunes along the shoreline indicate that the ridge is still eroding. Constructional platforms of beachrock are developed on the western shores of the major islands.

The Spearwood Ridge rises to 80 m above the floor of the Cockburn-Warnbro Depression. It is largely covered by Holocene dunes to the south but is exposed as a shoreline unit to the north. In places the main ridge is fronted to the west by a second, lower ridge, which rises to within a metre of present sealevel. This lower ridge is largely buried by Holocene marine sediments but it crops out on the seabed at Pt James.

Basins

Deep water areas (16-25 m depths) are termed basins. There are three basins: Warnbro Basin, Cockburn Basin and Madora Bay Basin. They are flanked by relatively steep slopes of the adjoining banks and platforms to the east, north and south, and by the Garden Island ridge to the west. Below about the 16m isobath in the Warnbro Basin and the 18 m isobath in Cockburn Basin, the basin floors slope gently to maximum depths of 19m and 25m respectively. The Madora Bay Basin exhibits an even more gentle slope from the adjoining banks to deeper water. The basin floors lack local bathymetric features and are devoid of seagrass meadow cover.

Banks

Banks are shallow water submarine geomorphic units, underlain by Holocene sediment, that extend across the entire width of the Warnbro-Cockburn Depression and form aprons and promontories around the subaerial sandy points in the area, and platforms around the intervening basins (Fig. 4). The two main banks in the area are the Rockingham and Becher banks. The (subaerial) Becher Point promontory, which extends part of the way towards the Garden Island Ridge from the Spearwood Ridge, is surrounded by a wide bank. In contrast, the Rockingham promontory, which links with the Garden Island Ridge at Point Peron, has smaller surrounding areas of banks. Between the two major east-west promontory axes, there is a narrow fringing platform (about 100 m wide) termed here the Warnbro Platform, around the Warnbro Sound shore. A similar platform is developed on the northern Rockingham Bank along the Cockburn Sound shore.

Seaward of the surf zone the surfaces of banks slope gently towards the basins to depths of about 6m. Below this depth contour the banks slope steeply (up to 20°) into the Warnbro Sound basin or the Cockburn Sound basin. Slopes from the Becher Bank south into the Madora Bay Basin are more gradual, only locally exceeding 5°. To the west the banks abut the flank of the Garden Island Ridge. The banks are surfaced by seagrass meadows, sand waves or sand flats. The more sheltered parts of bank surfaces support dense seagrass meadows. The Rockingham Bank supports particularly dense meadows while on the Becher Bank seagrass cover is more localized and patchy. Sandy shoals are also developed locally on the bank surfaces, and may be developed to a stage where they are continuously emergent.

Beach zone

This zone contains the active beach and beachridge (or foredunes). The morphology of the beach zone may vary significantly due to seasonal coastal processes and variable incident waves and currents. Subaerial beach profiles vary from narrow (10 m) and steep, to wide (about 100m) and gently sloping. The morphology of the contemporary beachridges varies from low (2-5 m) and only partially stabilized by vegetation, to high (6 to 10 to 22 m high) and well stabilized by vegetation (except in discrete active blowout areas).

Beachridge and dune plain

In plan the beachridge and dune plain (Quindalup Dunes of McArthur & Bettenay 1960) of the area is an irregular shape, with a straight, well-defined eastern margin where it abuts the Spearwood Ridge, and a cuspate or scalloped western margin. To the north, adjacent to Cockburn Sound, the plain narrows rapidly against the Spearwood Ridge (Fig. 1). To the south, the plain narrows gradually against the Spearwood Ridge before it terminates against the Peel-Harvey estuary exchange channel. The plain extends for 40 km along the coast and at its widest is 10 km. The mean elevation of the plain is 5m along the eastern margin and falls gradually to 2 m at the modern coast.

The surface of the plain is characterized by well defined linear beachridges and intervening swales (Fig. 2), that have been locally reworked into small parabolic dunes. There are over 100 beachridges and swales. The precise number is difficult to determine due to local acolian modification of the normally well defined ridges. Individual beachridges usually are 2 to 5m higher than the intervening swales, and 50 to 100 m apart. There is also a recurring pattern of higher beachridges that have a relief of 6 to 10m and, in a few instances, up to 22 m. Commonly these higher ridges and associated deep linear swales are separated by sets of about 3 to 6 lower ridges. Individual ridges and swales can be traced for over 20 km along the north-south length of the plain (Fig. 2). In plan the beachridge trends are parallel and concordant, except in the more seaward parts of the cuspate promontories and adjacent to the Spearwood Ridge. In these locations younger sets of beach-ridges obliquely truncate older sets.

The beachridges and swales generally are stabilized by vegetation. However, there has been some local aeolian modification and this varies from minor sculpturing, to complete reworking of ridges into blowouts and landward migrating parabolic dunes extending up to 750 m inland. Significantly, aeolian reworking is largely restricted to the higher-than-normal ridges; the regular lower relief beachridges remain mostly unaffected. The blowouts and parabolic dunes vary from unvegetated and actively forming to well stabilized by vegetation. However, the presently active blowouts and parabolic dunes occur at, or close to, the present coast.

Sedimentary facies

In the study area the variable incident waves and currents interact with the complex nearshore bathymetry to produce a broad spectrum of facies and lithotopes in which distinct suites of sediment types are formed. The sedimentary facies are, in order from basement and/or deep water upwards (Fig. 5): ridge aprons; basin; bank (incorporating slope, seagrass, sand wave and sand flat lithotopes): beach: and beachridge and dune.

Ridge apron facies

This facies forms aprons of sediment that lie adjacent to the limestone ridges. The dominant coastal processes are erosion of the Pleistocene aeolianite, and transport into deeper water. The sediments form wedges or ribbons of laminated, or bedded to cross layered, coarse to medium sand and gravelly, shelly sand. Sedimentary components are skeletons, derived from the adjoining rocky shores, lithoclasts and quartz.

Basin facies

The sediments of the basin facies form on the basin floors. These low energy deep water areas accumulate the slowly settled fine sediment entrained in the water from the more energetic bank environments. Only under extreme and short lived situations do waves or currents rework the basin floor. An exception is the Madora Bay Basin which is substantially more exposed to waves and currents. As a result sediment reworking is more frequent and can occur under moderate to heavy swells and strong wind driven currents.

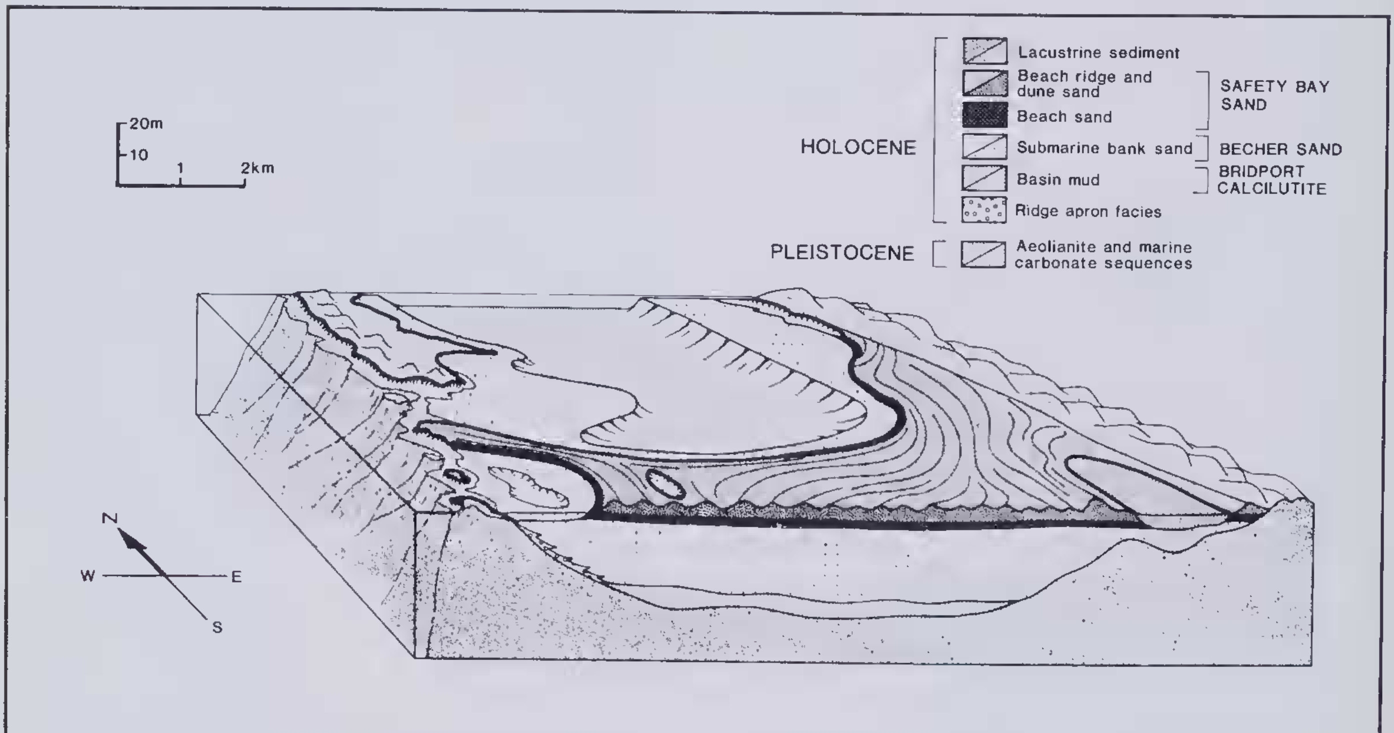

Figure 5 Three-dimensional diagram illustrating the relationship between geomorphic units, sedimentary facies and stratigraphic units.

Sediments of the basin facies generally are grey carbonate muds. The Madora Bay Basin sediments, in contrast, are fine to medium sand and are lighter grey. Bioturbation by infauna in all the sediments results in little or no preservation of primary sedimentary structures.

Bank facies

The bank facies includes the lithotopes of the bank slope, seagrass-covered surfaces, sand waves and sand flats.

Bank slope lithotope.—A distinct sedimentary lithotope occurs on the bank slopes to depths where the slopes merge with the basin floors. Transport mechanisms involve downslope gravity movement of sediment impelled over the bank edges by cross-bank transport. The steepness of the slopes and the marked decrease in wave and current energy downslope ensure that transport is unidirectional towards the basin.

The diagnostic characteristics of sediments in this lithotope are their degree of sorting and distribution down the slope. The sediments are grey, well sorted medium to fine sands, with fine sand on the lower slopes and medium sand on the upper slopes. The sediments are texturally and compositionally similar to the seagrass lithotope from which they are derived but lack large skeletal fragments. Slope-parallel laminations are formed and preserved in the upper slope sediments. Lower slope sediments are structureless due to a lack of textural variability or to bioturbation by infauna.

Seagrass lithotope.—The sediments of the seagrass lithotope accumulate under the extensive seagrass-covered bank surfaces. Sedimentary processes in the environment include *in situ* skeletal grain production, accumulation of skeletal grains in seagrass meadows, bioturbation by fauna, accumulation of seagrass material, cross-bank transport by waves and currents on surfaces not covered by seagrass meadow, and trapping/binding/baffling of sediment by seagrasses.

Sediments of the seagrass lithotope are sand and shelly sand varying to muddy sand and shelly sand. They are composed predominantly of sand-and gravel-sized skeletal material with variable seagrass detritus, fibres and carbonate mud. Locally, the sediments contain quartz sand, and adjacent to Pleistocene limestone outcrops there are substantial quantities of lithoclast sand. The sediments generally are grey, bioturbated and root-structured, and consequently there is a paucity of physical sedimentary structures. The grey coloration is due to staining by iron sulphide.

Sand wave/sand flat lithotope.—Sediments of the sand wave and sand flat lithotope form immediately seaward of the inshore zone. The seaward and depth limit of this lithotope, as defined by the occurrence of seagrass meadows, is variable and dependant on the local incident wave energy. In the protected environments of Cockburn Sound and Warnbro Sound the transition occurs at depths of 1 m, and the sedimentary products are almost indistinguishable from the lower beach facies. In the more exposed Madora Bay setting, the facies transition occurs at depths in excess of 3 m.

Sedimentation is dominated by the formation and migration of sand waves up to 1m in amplitude. The sediments of this lithotope are well sorted medium sands composed largely of skeletal fragments and lithoclasts. The quartz content is minor and significantly lower than the beach facies but higher than the seagrass lithotope. Sedimentary structures in the sediment include layering and cross layering with concordant sets reaching up to 1m in thickness; maximum dip angles of cross layering are about 15°.

Beach facies

The beach facies occurs along the shore of the active beach between the inshore zones and storm water level. The processes of sedimentation in this facies include wave and current transport, physical and biological swash zone processes, storm accumulation and erosion, and aeolian transport. The beach facies has been subdivided into several zones, *viz.*, backshore (berm), swash and shallow subtidal inshore, and sediments of the facies exhibit a lateral sequence of grain size and structures that correspond to processes operating within these zones (Semeniuk & Johnson 1982). Beach sediments consist of medium to coarse skeletal and lithoclast carbonate sand with a minor, variable quartz component. Usually the quartz content of the swash zone is significantly higher than adjoining zones and other facies. The sequence of sedimentary structures formed in each zone of the beach facies is: layered, medium sand and shelly sand in the backshore zone; laminated, medium to coarse shelly sands in the swash or foreshore zone, with bedded/laminated bubble sand in the upper swash zone; and cross- and trough-layered, medium to coarse sand and shelly sand in the inshore zone.

Beachridge and dune facies

The beachridge and dune facies occurs along the modern coastal zone adjoining the beach and is the product of aeolian transport inland from the beach. Sediments of the beachridge and dune facies are well sorted, medium and fine sand composed of rounded skeletal fragments, carbonate lithoclasts and minor well rounded quartz. Large scale cross layering is typical, except where vegetation has prevented the formation of structures or rootlets have disrupted them.

Stratigraphy

Components of the stratigraphy have been described previously by Passmore (1970) and Semeniuk & Searle (1985b). The area contains the type localities for 4 Quaternary formations relevant to this study: 1)Safety Bay Sand (Passmore 1970, redefined by Semeniuk & Searle 1985b); 2)Becher Sand (Semeniuk & Searle 1985b); 3)Bridport Calcilutite (Semeniuk & Searle 1987); and 4)Cooloongup Sand (Passmore 1970). In addition, the Tamala Limestone (Playford *et al.* 1976) occurs in the area. For purposes of this paper the Tamala Limestone will be considered to be the foundation or basement unit in the area.

Pleistocene-Holocene contact

The Pleistocene-Holocene contact in this area is an unconformity interface cut into Tamala Limestone, or yellow quartz sand (Cooloongup Sand), or ?Plio-Pleistocene mud. Thus the unconformity is coincident with the buried Pleistocene ridge-and-depression palaeotopography (Figs 5 & 6). The Holocene sequence in the main abuts a steep cliff cut into Tamala Limestone along the Spearwood Ridge to the east, and pinches out against, or onlaps Tamala Limestone along the Garden Island Ridge to the west. In the depression between the two ridges the unconformity surface is marked by calcreted Tamala Limestone with variable cover of (yellow) quartz sand. In the Singleton Beach area (transect 3), the Holocene deposits rest on a grey clay deposit, determined by palynology to be ?Plio-Pleistocene (J. Backhouse, pers. comm.).

Holocene units

The Pleistocene/Holocene unconformity is overlain by a variety of Holocene units. These units, described in order from the Pleistocene-Holocene contact upwards, include (Table1 and Figs 5, 6 & 7): local rocky shore deposits; local estuarine mud; Bridport Calcilutite; Becher Sand; and Safety Bay Sand.

The main Holocene units in the area are the Bridport Calcilutite, Becher Sand and Safety Bay Sand. Rocky shore deposits are confined to the flanks of the mainland shore and the Garden Island Ridge and usually are buried by younger Holocene units. Local deposits of shelly estuarine mud (referable to the Leschenault Formation: Semeniuk 1983) occur as thin layers in the former hollows in the Cockburn-Warnbro Depression; these deposits also are buried by younger Holocene units. The stratigraphic relationships of the various units and their relationship to geomorphic units is summarized in Figure 5. The bulk of the Rockingham-Becher Plain is underlain by the Safety Bay Sand and Becher Sand. There is a consistent stratigraphic relationship between these two formations throughout most of the area wherein the Becher Sand forms the contemporary banks and extends under the beachridge plains to underlie the Safety Bay Sand. In the San Remo area (transect 4, Fig. 6), however, the Safety Bay Sand overlies a sheet of shelly (rocky shore) deposit and locally, an estuarine sediment unit.

The Bridport Calcilutite consists of grey muddy carbonate sediment which formed in the basin facies. The unit occupies former depressions in the underlying palaeotopography and is the lowermost unit of the main Holocene deposits, overlying either the other minor Holocene units or the Pleistocene units. The Becher Sand is composed of sediment formed in the bank facies (Semeniuk & Searle 1985b): it is mostly grey, bioturbated sand and shelly sand with local seagrass fibre.

The Safety Bay Sand is composed of sediment formed in the beach, beachridge and dune facies. For purposes of stratigraphy and palaeo-environmental interpretations the Safety Bay Sand is subdivided into a beach (littoral) facies and a beachridge/dune (aeolian) facies (following Semeniuk & Searle 1986b). A notable feature of the sediments of the Safety Bay Sand is that they typically exhibit a small scale stratigraphic sequence of structures, lithology and grainsize, reflecting depositional environmental gradients within the facies and transitions between the facies (see Semeniuk & Johnson 1982; and Woods & Searle 1983). This stratigraphic sequence is consistently encountered ubiquitously beneath the beachridge plain; from the surface the sequence is (Fig. 7):

- cross-layered to structureless aeolian beachridge and dune sand with *Spirula* and *Sepia* skeletons near the base, grading down into
- horizontal to seaward dipping, layered medium sand and shelly sand, with *Spirula* and *Sepia* skeletons and *Ocypode* burrows (backshore unit)
- seaward-dipping laminated medium to coarse shelly sand with *Donax* and *Glycymeris* (swash unit), and locally preserved bubble sand in the upper part,
- cross-and trough-layered medium and coarse sand and shelly sand (inshore unit).

The base of the sequence rests on bioturbated to crudely layered sand, shelly sand and muddy sand of the Becher Sand.

In the nearshore submarine area north of Mandurah the stratigraphy consists of a sheet of fine/medium sand about 1.5m thick, overlying a 0.5m thick gravel deposit of shells (Fig. 7). This gravel layer also occurs under the Safety Bay Sand along transect 4 (Fig.6) in the San Remo area. The-shells are a mixture of fauna derived from environments of rocky shores, seagrass meadows, beach zones and an estuary.

Age structure of Rockingham-Becher plain

The materials used for radiocarbon analyses and their ages are described in Table 2. The radiocarbon results are used to determine: the initiation and history of Holocene

Table 1

Description of Holocene Stratigraphic Units

Unit	Description	Thickness	Stratigraphic Relationships	Occurrence
Safety Bay Sand	prism, or sheet of laminated, x-laminated to structureless sand and shelly sand	mostly 2-6 m	sharp contact with underlying Becher Sand; locally sharp contact with rocky shore deposits	underlies much of the plain and forms the sub-aerial surface of the plain
Becher Sand	wedge or prism of bioturbated, structureless to crudely layered grey shelly sand, sand and muddy sand; local seagrass fibre	up to 20 m	sharp contacts with underlying Bridport Calcilutite and with overlying Safety Bay Sand; locally gradational contact with underlying Leschenault formation or rocky shore deposits, or Cainozoic mud	underlies much of the plain; forms contemporary surface of the Rockingham and Becher banks
Bridport Calcilutite	wedge, or ribbon, or sheet of structureless carbonate mud and shelly	usually 2 m thick, up to 6 m thick	gradational contact with underlying Cooloongup Sand and Leschenault Formation; sharp contact with overlying Becher	occurs as buried deposit towards middle and western portion of the plain; forms contemporary surface in Warnbro Sound
Leschenault Formation	lens of grey/black clay mineral mud and muddy sand with estuarine shell assemblage	<1 m	gradational contact with underlying Cooloongup Sand; or sharp contact, marked by pebbles with Tamala Limestone overlain gradationally by Becher Sand or Bridport Calcilutite	in former deep depressions underlying the Rockingham-Becher Plain
Rocky shore deposits and ridge apron deposits	sheet and wedge shaped unit of gravelly and shelly lithoclastic skeletal sand	<1 m	overlies Tamala Limestone; overlain by Becher Sand or Safety Bay Sand	Usually located on flank of Spearwood Ridge and on flank of Garden Island Ridge but also forms basal sheet in the San Remo area

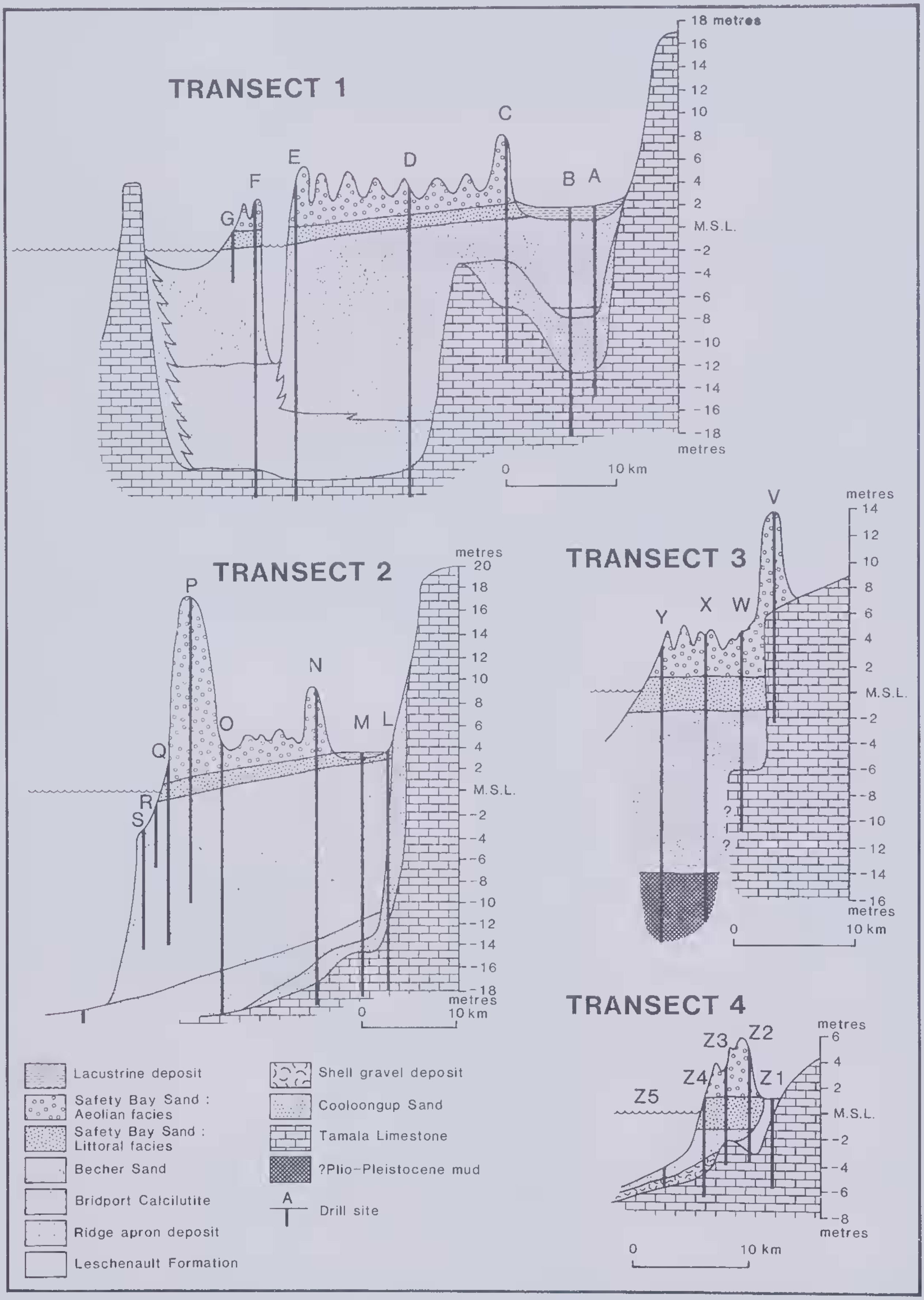

Figure 6 Stratigraphic profiles along 4 east-west transects. Location of transects and drill sites are shown in Figure 3.

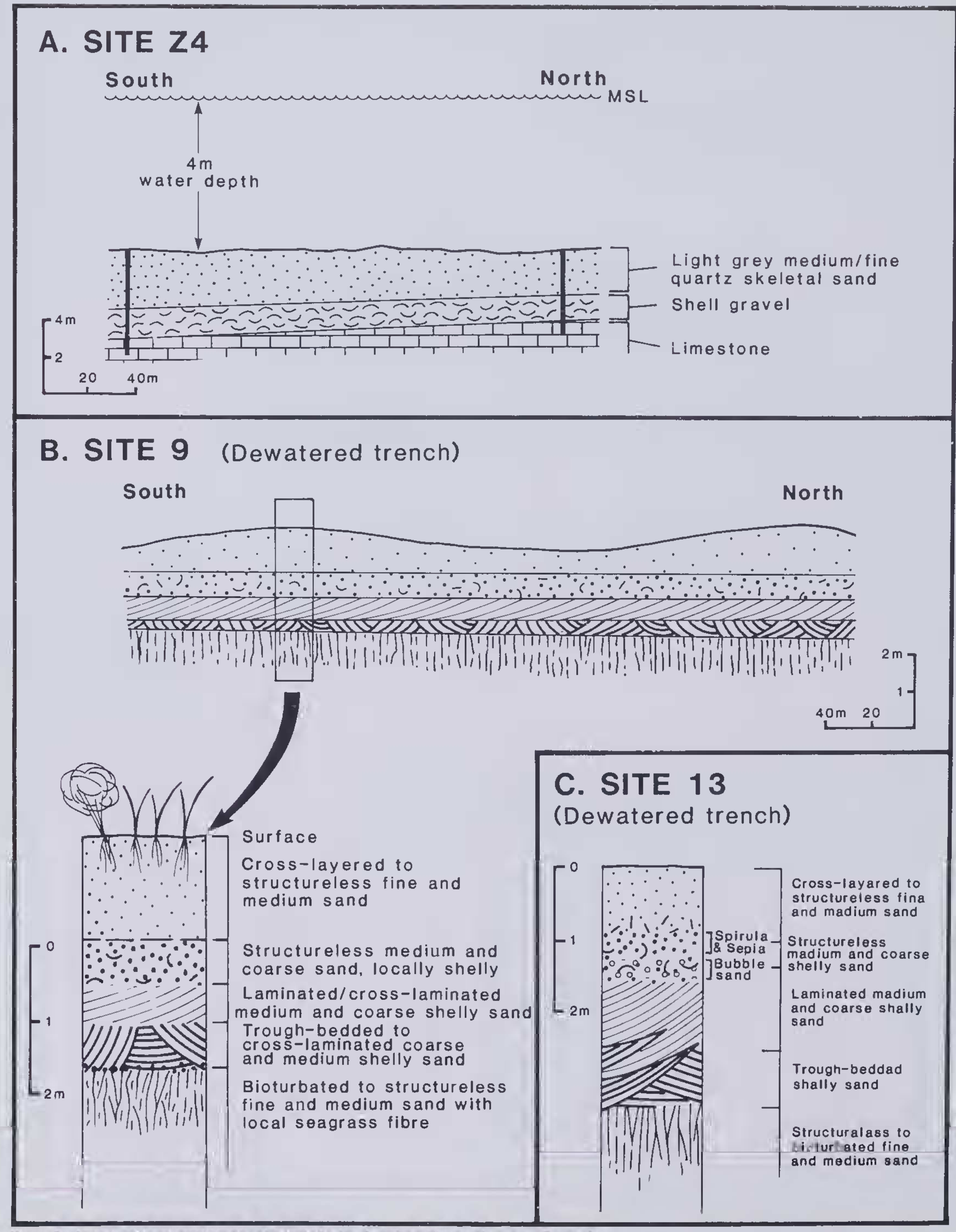

Figure 7 Details of local stratigraphy at selected sites. Location of sites shown on Figure 3.

sedimentation in this area; the rate of vertical accretion of the sequences; the age structure of the accretionary plain and the development of its geomorphic features; and the history of sealevel during the Holocene. Most of the ages returned from the samples were consistent within the context of their stratigraphic and geographic setting. However, some dates, particularly from peaty wetlands, were anomalous. These will be described and discussed in a future study (Semeniuk *et al.* in prep).

Table 2

Description of Material used in Radiocarbon Dating

Radio-carbon sample site no. Fig.3)	Sample no. this paper	Field no.*	Labor-atory no.	Stratigraphic setting	Rationale for sample	Height (m) of SL indicator if applic able	Sample type**	Age in C14 yrs not C13 corrected	Age in C14 yrs BP C13 corrected	dC13/dC12 (o/oo)
1	1	VCSRG29	GX12028	North shore lake Cooloongup; shelly layer in top of Becher sand	Age of top marine sands	-	Donax	5 395	5 800 ± 305	0.9
2	2-1	VCSRG25	GX12024	West shore lake Cooloongup; shelly beach layer	Age of beach horizon	not determined	Donax & Donacilla	6 075	6 470 ± 375	0.3
	2-2	VCSRG30	GX12029	West shore lake Cooloongup; shell at base of Holocene sequences contact between Becher Sand and Cooloongup Sand	Age of base of the Holocene sequence	-		7 235	7 670 ± 360	1.2
3	3	SH-22	GX11587	Shelly beach layer	Age of beach horizon	+2.4	Donax	5 295	5 700 ± 190	1.0
4	4	SH-10	1-11-978	Shelly beach layer	Age of beach horizon	+2.4	Donax	5 660 ± 110	-	-
5	5	SH-11	1-11-979	Shelly beach layer	Age of beach horizon	+ 1.9	Donax	5 440 ± 110	-	-
6	6	VCSRG24	GX12023	Shelly beach layer	Age of beach horizon	+1.5	Donax	3 670	4 080 ± 250	1.1
7	7-1	VCSRG23	GX12022	Shelly beach layer	Age of beach horizon	+0.5	Donax	2 340	2 760 ± 220	1.9
	7-2	RW15-16	GX12904	Shelly horizon contact between base Becher Sand and Bridport Calcilutite	Age of encroachment of Becher Sand seagrass bank	-	Seagrass gastropod fauna	2 774	3 210 ± 145	2.8
	7-3	RW22-23	GX12903	Shelly horizon at base of Bridport Calcilutite	Age of base of Holocene sequence	-	Pecten shells	6 120	6 535 ± 225	1.5
8	8	SH-21	GX11586	Shelly beach layer	Age of beach horizon	+0.95	Donax	3 892 ± 245	-	1.5
9	9	SH-20	GX11585	Shelly beach layer	Age of beach horizon	+0.7	Donax	2 224 ± 135	-	2.0
10	10	SH-14	1-12-362	Shelly beach layer	Age of beach horizon	+0.7	Donax	2 790 ± 90	-	0.4
11	11	SH-12	1-11-980	Shelly beach layer	Age of beach horizon	not determined	Donax	2 890 ± 85		-
12	12	VCSRG27	GX12026	Shelly beach layer	Age of beach horizon	+2.6	Donax	6 645	7 040 ± 390	0.3

Table 2 Description of Material used in Radiocarbon Dating .... cont.

Radio-carbon sample site no. Fig.3)	Sample no. this paper	Field no.*	Labor-atory no.	Stratigraphic setting	Rationale for sample	Height (m) of SL indicator if applic able	Sample type**	Age in C14 yrs not C13 corrected	Age in C14 yrs BP C13 corrected	dC13/dC12 (o/oo)
13	13-1	SH-9	1-11-977	Shelly beach layer	Age of beach horizon	+2.5	Donax	6 380 ± 115	-	
	13-2	VCSRG26	GX12025	Upper level of Becher Sand	Age of Becher Sand upper level	-	Seagrass peat	7 395	7 560 ± 360	-14.6
	13-3	WALY16-17	GX12906	Base of the Holocene -estuarine shell	Age of the base of the Holocene sequence	-	Katelysia	7 980	8 365 ± 375	-0.6
14	14-1	VCSRG28	GX12027	Shelly beach layer	Age of beach horizon	+2.6	Donax	6 440	6 825 ± 495	-0.4
	14-2	WALY.W. 14-15	GX12905	Mid Becher Sand	Age of Becher Sand	-	Donax	7 510	7 920 ± 105	1.3
15	15-1	HR5-1	GX11882	Shelly beach layer	Age of beach horizon	+1.0	Donax	2 930	3 340 ± 215	1.8
	15-2	HR5-3	GX11883	Becher Sand 6m below AHD	Age of Becher Sand	-	Donax	3 035	3 445 ± 220	1.2
	15-3	HR5-6	GX11885	Becher Sand 14m below AHD	Age of Becher Sand	-	Donax	3 220	3 630 ± 225	1.2
16	16-1	HR4-4	GX11879	Becher Sand 1.5m below AHD	Age of Becher Sand	-	Donax	1 655	2 070 ± 210	1.8
	16-2	HR4-8	GX11881	Becher Sand 11 m below AHD	Age of Becher Sand	-	Donax	2 295	2 705 ± 210	1.3
17	17-1	HR3-1	GX11872	Shelly beach layer	Age of beach horizon	0.0	Donax	1 010	1 425 ± 150	1.7
	17-2	HR3-2	GX11873	Becher Sand 2 m below AHD	Age of Becher Sand	-	Donax	1 230	1 655 ± 160	2.2
	17-3	HR3-3	GX11874	Becher Sand 4.5 m below AHD	Age of Becher Sand	-	Donax	1 400	1 815 ± 160	1.6
	17-4	HR3-6	GX11876	Becher Sand 11 m below AHD	Age of Becher Sand	-	Donax	2 080	2 485 ± 205	0.9
	17-5	HR3-8	GX12908	Becher Sand 16m below AHD	Age of Becher Sand	-	Seagrass gastropods & bivalves	2 145	2 550 ± 160	0.8
18	18-1	HR2-1	GX11869	Surface Becher Sand	Age of Becher Sand	-	Glycymeris & Mactra	modern	modern	1.8
	18-2	HR2-3	GX11870	2 m below surface	Age of Becher Sand	-	Seagrass gastropods	670	1 085 ± 185	1.6
	18-3	HR2-4	GX11871	3 m below surface	Age of Becher Sand	-	Seagrass gastropods	985	1 420 ± 190	3.0

Table 2 Description of Material used in Radiocarbon Dating .... cont.

Radio-carbon sample site no. Fig.3)	Sample no. this paper	Field no.*	Labor-atory no.	Stratigraphic setting	Rationale for sample	Height (m) of SL indicator if applic able	Sample type**	Age in C14 yrs not C13 corrected	Age in C14 yrs BP C13 corrected	dC13/dC12 (o/oo)
19	19-1	HR1-1	GX11866	Surface Becher Sand	Age of Becher Sand	-	Glycymeris	modern	modern	1.6
	19-2	HR1-3	GX11867	Beach sand 2 m below surface	Age of Becher Sand	-	Seagrass gastropods	150	565 ± 170	1.5
	19-3	HR1-5	GX11868	Beach sand 5 m below surface	Age of Becher Sand	-	Seagrass gastropods	160	575 ± 170	1.5
	19-4	HR1-9	GX12907	Beach sand 8.5 m below surface	Age of Becher Sand	-	Seagrass gastropod fauna & bivalves	990	1415 ± 145	2.3
20	20	SH-8	1-11-964	Shelly beach layer	Age of beach horizon	+1.6	Donax	4 180 ± 105		0.41
	20R	SH-8R	1-12-557	Shelly beach layer	Age of beach horizon	+1.6	Donax	4 450 ± 90		-
21	21	SH-5	1-11-777	Shelly beach layer	Age of beach horizon	+1.75	Donax	4 745 ± 95		-
22	22	SH-4	1-11-776	Shelly beach layer	Age of beach horizon	not determined	Donax	3 525 ± 95		-
23	23	SH-2	1-11-774	Shelly beach layer	Age of beach horizon	+0.3	Donax	1 720 ± 80.		-
24	24	SH-3	1-11-775	Shelly beach layer	Age of beach horizon	+0.9	Donax	3 495 ± 95		-
25	25	SH-1	1-11-773	Shelly beach layer	Age of beach horizon	+0.0	Donax	600 ± 75		-
26	26	SH-6	1-11-962	Shelly beach layer	Age of beach horizon	+0.0	Donax	375 ± 75		0.74
27	27	SH-7	1-11-963	Shelly beach layer	Age of beach horizon	+0.0	Donax	contemporary		0.46
28	28	SiB3:5-6	GX12628	Shelly beach layer	Age of beach horizon	+1.0	Donax	2 285	2 720 ± 185	1.3
29	29	SiB2:6-8	GX12627	Shelly beach layer	Age of beach horizon	+0.0	Donax	1 450	1 880 ± 150	1.1
30	30	SiB1:3-4	GX12626	Shelly beach layer	Age of beach horizon	+0.0	Donax	205	630 ± 175	0.6
31	31	SSRO (NMB)	GX12622	Shelly estuarine mud	Age of estuarine sand flat	+2.2	Katelysia and Sanguinolaria	6 535	6 910 ± 235	-2.1
32	32	SSR1:7-8	GX12623	Shelly gravel layer at base of Holocene sequence	Age of estuarine conditions	-	Katelysia and Sanguinolaria	6 675	7 050 ± 115	-2.3

Table 2 Description of Material used in Radiocarbon Dating .... cont.

Radio-carbon sample site no. Fig.3)	Sample no. this paper	Field no.*	Labor-atory no.	Stratigraphic setting	Rationale for sample	Height (m) of SL indicator if applic able	Sample type**	Age in C14 yrs not C13 corrected	Age in C14 yrs BP C13 corrected	dC13/dC12 (o/oo)
33	33-1	SSR3: 8-9	GX12902	Shelly beach layer	Age of beach horizon	+0.5	mixed Donax Glycymeris & Donacilla	3 060	3 475 ± 160	1.6
	33-2	SSR3: 10-11; Est	GX12625 sequence	Estuarine fauna over-lying unconformity	Age of estuarine conditions	-	Katelysia Sanguinolaria	1 735	2 170 ± 205	1.2
	33-3	SSR3: 10-11; R.Sh.	GX12624	Rocky shore fauna on unconformity on limestone	Age of marine rocky pavement	-	Ninella, chamiids	2 520	2 960 ± 250	1.6
34	34-1	MH3 1.5m	GX12682	Seagrass fauna in shell gravel 1.5 m below surface	Age of seagrass bank deposits	-	Mactra	3 240	3 645 ± 160	0.7
	34-2	MH3 1.5 m	GX12683	Rocky shore fauna in shell gravel 1.5 m below surface	Age of rocky shore deposits	-	Ninella & chamiids	5 335	5760 ± 335	2.0
	34-3	MH3 1.5 m	GX12685	Beach fauna in shell gravel 1.5m below surface	Age of beach deposit	-	Glycymeris & chamiids	5 850	6 305 ± 205	2.6
	34-4	MH3 1.5 m	GX12686	Estuarine fauna in shell gravel 1.5 m below surface	Age of estuarine deposits	-	Katelysia	6 540	6 950 ± 230	1.1
	34-5	MH3 1.5 m	GX12681	Rocky shore fauna in shell gravel 1.5 m below surface	Age of rocky shore deposits	-	Oyster	7 025	7 420 ± 260	0.5

Footnotes:

* GX numbers: Kreuger Geochron Laboratories

1-11-98 numbers: Teledyne Laboratories

** Sample type Type of sample used and brief description of sample preparation

1. Donax; processing carried out as outlined by Woods & Searle (1983) and Searle & Woods (1986).

2. Bivalves such as Glycymeris and Mactra from seagrass bank assemblages; samples chosen for processing were clean, fresh, lustreous specimens lacking in adhering cements and dull patches.

3. Gastropods from seagrass bank assemblages usually large specimens of Prothalotia and allies; tip of spire of the large specimens of the gastropods was removed by pliers and the hollow body whorl was flushed clean of any adhering sediment to provide clean samples, (without sediment packed in body whorls) for radiocarbon analyses.

4. Seagrass peat; sample was oven dried and wrapped in aluminium foil for despatching.

As outlined in Woods & Searle (1983) and Gillespie & Polach (1979), it is necessary to consider both C13 corrections and the reservoir effects when reporting radiocarbon dates. Gillespie & Polach (1979) have considered the reservoir effects on dating Australian marine shells, and included material from southwest Australia in their study; they determined a mean correction value of 450±35 years, to be subtracted from any uncorrected date. Isotopic fractionation was determined for most of the samples used in this study (Table 2). Most results were close to the expected value of 0±1%, d13C/d12C predicted by Stuiver & Polach (1977) for marine carbonate, and therefore an age correction factor of 410±70 years is applicable. This value, when added to a radiocarbon age, approximately cancels the correction for the reservoir effect. Because the major correction factors cancel when dating Australian marine shells, then the reported dates in ears BP can be used directly.

Initiation of Holocene sedimentation

The results from radiocarbon dating confirm that the Bridport Calcilutite, the Becher Sand and the Safety Bay Sand are wholly Holocene (Table 2). The Holocene record begins at about 8000 C14 yrs BP. Age determinations at site M (Fig. 8) adjacent to the Spearwood ridge, the most eastern sampling sites, indicate that the post-glacial marine transgression had reached this shoreline by 7980 C14 yrs BP and that beach conditions were established by 6645 C14 yrs BP.

Vertical accretion rates

Radiocarbon dates from the basin, bank and beach units provide a 3-dimensional picture of the age structure of the Holocene sediments of the Rockingham-Becher Plain. Ages from sites A, C, L, M and N (Fig. 8) indicate that between about 8000 and 6500 yrs BP, the sediments under the Rockingham Bank shoaled from deepwater to within about 2m of the former sealevel. Ages from sites 0, P, Q, W, X and Y indicate that the Becher Bank is a younger sedimentary accumulation.

Age structure of plain

Beachridges mark successive shoreline positions and in effect represent isochrons. When combined with the radiocarbon data, they enable the history of shoreline progradation to be determined. Radiocarbon ages of the shells from the beach facies at various sites indicate that the age structure of the plain is reasonably internally con-

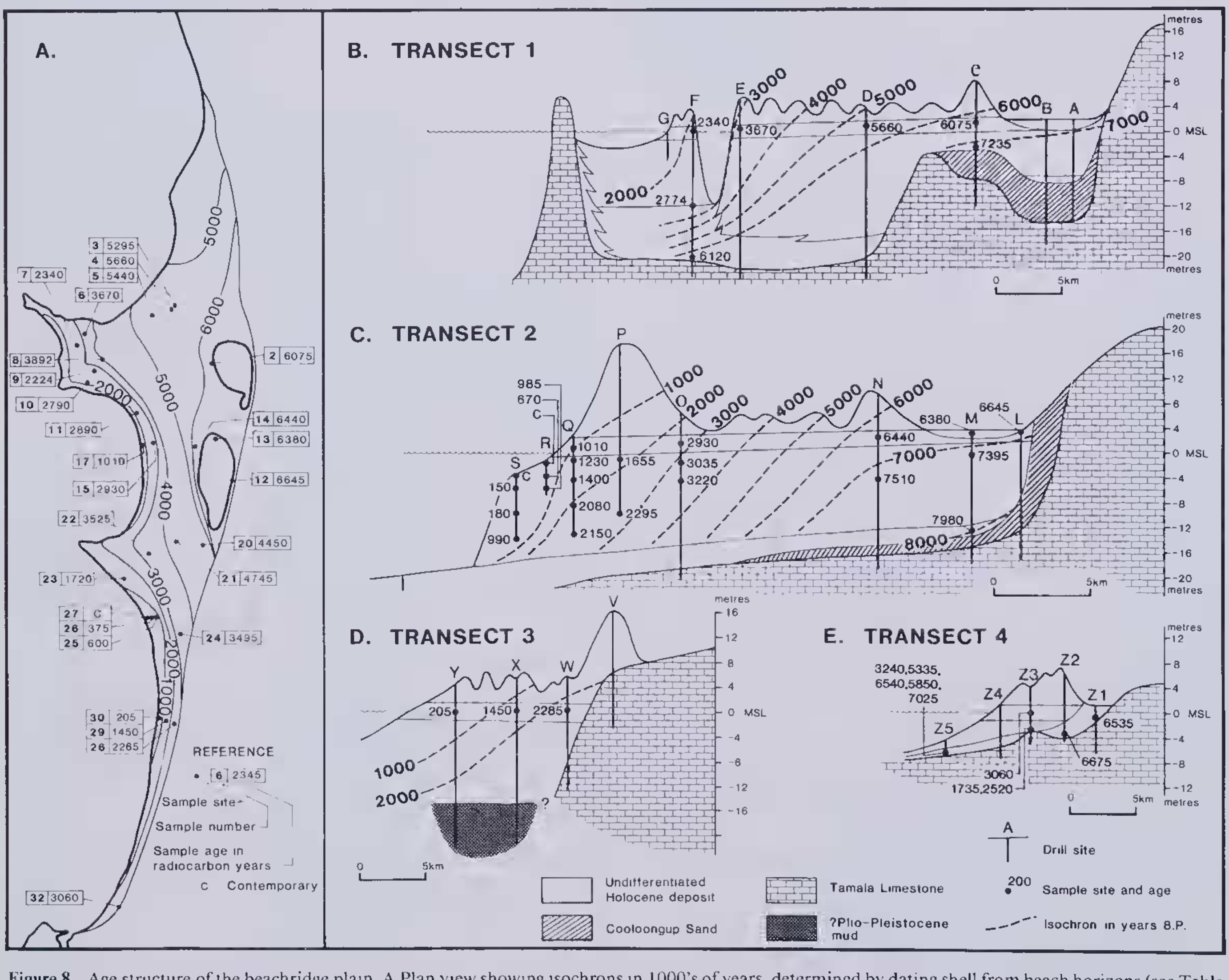

Figure 8 Age structure of the beachridge plain. A Plan view showing isochrons in 1000's of years, determined by dating shell from beach horizons (see Table 2); locations of sample sites shown in Figure 3. B Cross sections through the 4 transects showing interpreted isochrons based on radiocarbon results; sample sites, sample depths and radiocarbon ages are shown on cross sections; Table 2 describes sample type in more detail.

sistent. The beach facies ranges in age from about c 6600 C14 yrs adjacent to the Spearwood Ridge to contemporary along parts of the modern shore (Fig. 8).

Age of shell gravel

The shell gravel in the nearshore submarine environment north of Mandurah and beneath the Safety Bay Sand at San Remo provided a range of ages for the various shell components (samples 32, 33-2, 33-3, 34-1, 34-2, 34-3, 34-4, 34-5). Rocky shore shells, indicating open marine conditions, gave ages of 2500, 5335 and 7025 C14 yrs BP; estuarine shells indicate that estuarine conditions existed at the site at various times between 6540 and 1700 C14 yrs BP; and seagrass fauna and beach fauna gave ages of 3240 and 1900 C14 yrs BP.

Sealevel history

Beneath the prograded beachridge plains there is a distinct horizontal stratigraphy with beachridge/dune sediments overlying beach sediments which, in turn, overlie bank sediments (Figs 6 & 7). Contemporary beach (swash zone) sediment, can be related to MSL, and former beach sediments now buried inland provide an indication of the position of former sealevel. In addition, the contact between the Safety Bay Sand and Becher Sand represents a stratigraphic interface between sediments of the beach and bank facies and also is useful as an indicator of relative MSL (Searle & Woods 1986). The modern contact between Safety Bay Sand and Becher Sand is approximately 0.5-1.5 m below MSL in protected embayments (in Cockburn Sound and Warnbro Sound), and up to 2.0 m below MSL along more exposed coasts; this interface never forms above MSL.

The elevations of former sealevel indicators were determined mostly in a 10 km long continuous trench (the Cape Peron pipeline route), or dewatered pits (Fig. 3), or from precisely recovered drill core material (Fig. 3). The middle of swash zone sediments in the sequence was considered to be the best indicator of former sealevel. In some shallower pits (where deep excavations were not possible because of groundwater problems), only the backshore sediments were exposed. However, the elevation of former MSL was interpreted relative to the top of the backshore sediments using the average thickness difference (1.2 m) between sediments of the mid swash and the top of the backshore shown at the present coast and in the deeper pits.

In the stratigraphic sequence beneath the beachridge plain the sheet of swash zone sediments rises gradually to reach an elevation of +2.5 m above MSL about 10km inland adjacent to the Spearwood Ridge, implying a relative MSL of about +2.5 m earlier in the Holocene i.e. 6645 C14 yrs BP. The elevation of the top of the bank sands, (*i.e.* the interface between beach and bank sediments), beneath the plain also rises gradually to reach an elevation of between +1.2 to 1.8 m inland, confirming a relative sealevel high in the order of up to +2.5 m above MSL earlier in the Holocene.

The dating of sealevel indicators at various sites enables a reconstruction of sealevel history for the interval of the Holocene *c* 8 000 C14 yrs BP to the present (Searle & Woods 1986, Semeniuk & Searle 1986b). The data pertaining to sealevel indicators, their ages and their stratigraphic elevation or position relative to present MSL are presented in Table 2. The elevation of the mean sealevel indicators and their radiocarbon ages are shown in Figure 9.

A sealevel history curve derived from these data shows that the Holocene sealevel on this coast reached an elevation of at least +2.5 m some 7000 C14 yrs BP, and then gradually declined, reaching the present level shortly after

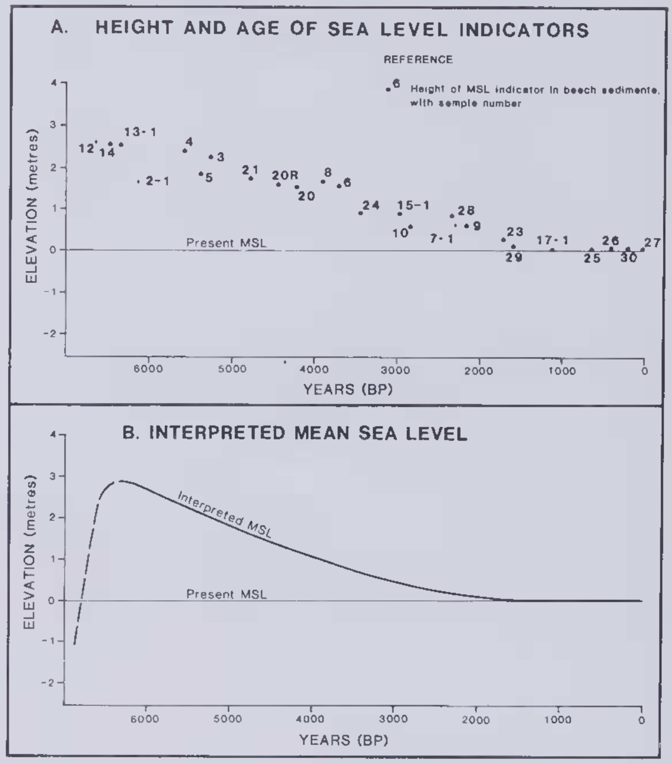

Figure 9 A Graph showing elevation of sealevel indicators and radiocarbon age for a variety of shell samples from beach horizons.
B Interpreted mean sealevel history for the past 7000 yrs.

1000 yrs BP (Fig. 9). Sealevel subsequently has remained close to present datum. Semeniuk & Searle (1986b), however, also pointed out potential small scale sealevel oscillations in the interval between 5000-4000 C14 yrs BP. This study has not excluded the possibility of such small scale fluctuations in that time interval.

The reconstruction of local sealevel history in this area is in general agreement with previous local data (Hassell & Kneebone 1960, Fairbridge 1961, Playford & Leech 1977) in that there is evidence for a higher relative MSL during the Holocene, but, as discussed by Searle & Woods (1986), no evidence was found for the ±3 m oscillations proposed by Fairbridge (1961). Further, more detailed investigations are still required to assess the possibility of smaller (±1 m) oscillations over the entire interval of 7000 C14 yrs BP to the present.

The sealevel history of this study differs from interpretations obtained from some other localities in the Northern Hemisphere and eastern Australia which do not show a significant rise in level above present datum, and elsewhere along the Western Australian coast (Jelgersma 1966, Curray 1960, Shepard 1963, Milliman & Emery 1968, Morner 1976, Thom *et al.* 1969, Thom & Chappell 1975, Semeniuk & Searle 1986a). Searle & Woods (1986) originally suggested that there were two possible explanations for the apparent discrepancy: hydro-isostatic responses (Chappell 1974, Clark *et al.* 1978) or local tectonism (Playford & Leech 1977, Semeniuk & Searle 1986b). The results of this study would appear to be consistent with hydro-isostatic displacement, the sense and magnitude of which compare favourably with results reported by Chappell *et al.* (1982) and Chappell (1983) for northeastern Australia. However, local tectonism seems more likely to explain the variability in sealevel record. Playford & Leech (1977) noted that there has been up to 300 m of uplift of the Yilgarn Block since the Eocene, and suggested local tectonism as one of the causes for the elevated sealevel record on this coast. Semeniuk & Searle (1986b) recently discussed the significance of local tectonism in producing a variable sealevel history within accretionary sequences between Bunbury and Whitfords.

Reconstruction of palaeogeography during the Holocene

Philosophy of approach

The stratigraphy and age structure of the Rockingham-Becher Plain can be used to provide a synthesis of the geomorphic evolution of the system. This section attempts to present a simplified reconstruction of palaeogeography during the Holocene between 8000 C14 yrs BP and the present. The synthesis is based on:

- the stratigraphy and its palaeo-environmental significance: the beach facies of the Safety Bay Sand are littoral zone sediments; the beachridge and dune facies of the Safety Bay Sand are aeolian sediments; the Becher Sand has formed in submarine bank environments, encompassing seagrass, slope, sand wave and sand flat lithotopes; and the Bridport Calcilutite was deposited in protected basins;
- the age structure of the various stratigraphic units, and specifically the beach sediments beneath the plain;
- the assumption that a beachridge line represents a synoptic picture of the shoreline, and that the radiocarbon age of shell material from the beach facies provides an age of the overlying beachridge shoreline;
- a modified interpretation of Searle (1984) for the geomorphic evolution of the coastal system, i.e., islands and reefs of the offshore Pleistocene aeolianite ridges erode and degrade, whereas Holocene banks and beachridge plains are depositional and progradational (Fig. 10).

Searle (1984) concluded that Holocene sediment accretion in this region has been controlled by the interaction of the shelf wave climate with the complex and eroding ridge-and-depression bathymetry, the abundant sources of sediment, and the evolving bank structures. Under the influence of prevailing swell and wind waves, there has been net northward sediment transport along the exposed seaward face of the Garden Island Ridge and mainland Spearwood Ridge. Where the offshore ridge sheltered the mainland shore, longshore transport diminished as the Garden Island ridge gained prominence. As a result the northern littoral drift accumulated in the sheltered area behind the south of Garden Island to form a submarine bank and a series of recurved spits (*ie* a tombolo effect).

The Garden Island Ridge also acted and still functions as a perforate barrier allowing a portion of the incident waves through gaps and passages into the otherwise shel-

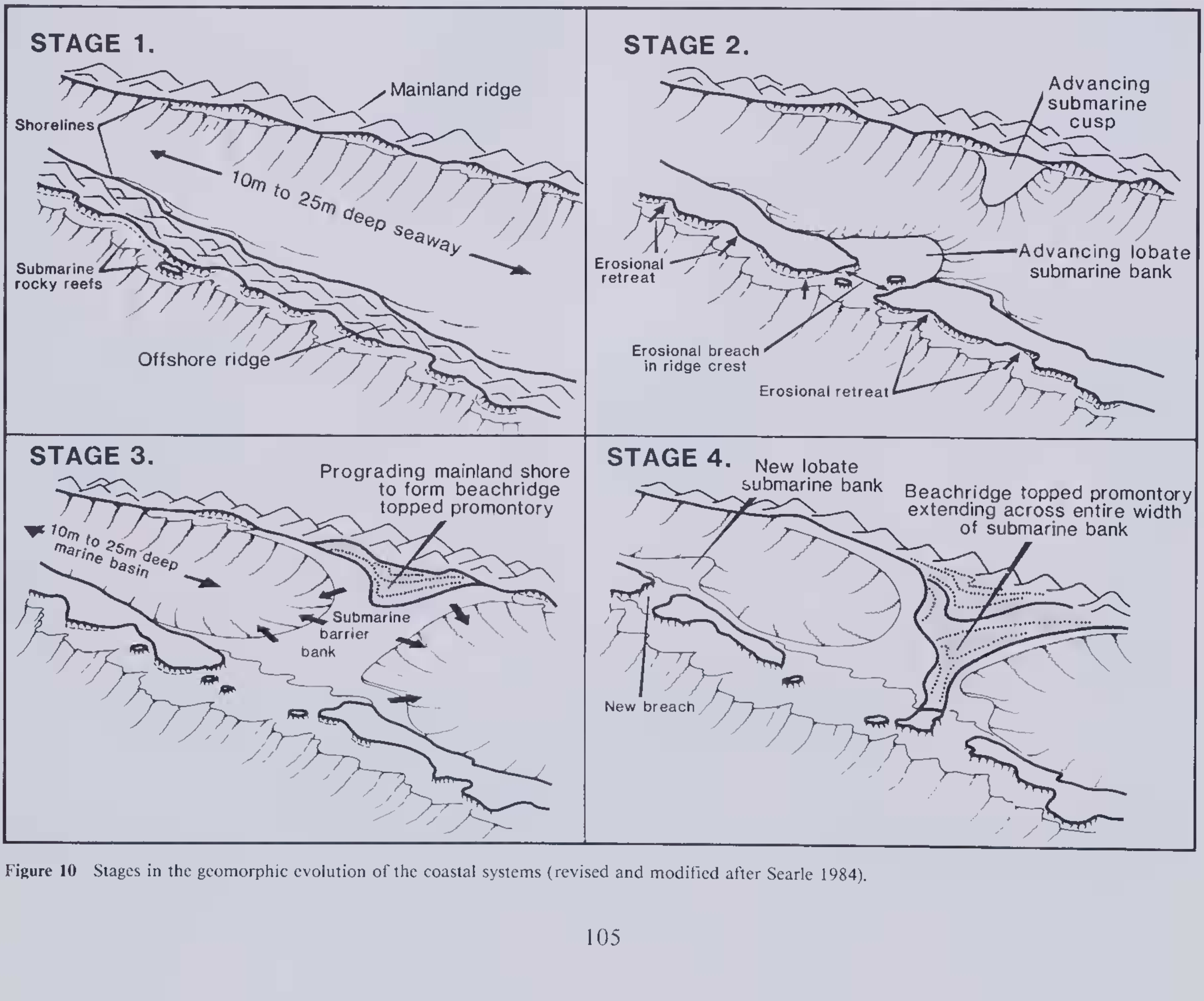

Figure 10 Stages in the geomorphic evolution of the coastal systems (revised and modified after Searle 1984).

tered depressions. Waves passing through breaches in the ridge divert sediment from the transport pathway on the seaward side of the ridge transporting it eastward into the adjacent depression to form lobate submarine banks. Onshore Holocene sediment transport has been largely influenced by these loci of transmitted wave energy to form well defined submarine banks.

Refraction over the banks causes convergence of waves that have passed through the ridge crest toward the central axis of the banks. Thus sediment impelled shoreward is contained within the bank axis. The convergence of waves also causes a local accumulation of littoral sediment on the mainland shore. Where the submarine bank lobe has accreted to the extent that it perturbates the swell wave pattern and disrupts the longshore transport pattern on the mainland coast, it causes the mainland to accrete as a large sandy submarine "cusp" toward the advancing bank. When the bank and cusp meet, progradation of the mainland shore across the submarine bank surface is initiated and is centred on the bank-cusp axis. As a result banks become capped with an extensive cuspate beachridge plain. In contrast, the coastline *between* adjacent banks progrades much more slowly. Coincident with bank accretion there is continuing erosion and widening of breaches in the Garden Island Ridge culminating in the reduction of the island chain to a series of submerged reef lines.

The palaeogeographic reconstruction presented in this paper thus incorporates the large scale evolution of banks and concommittant erosion of ridges. As such the paper provides an alternative to palaeogeographic reconstruction of the Holocene evolution as presented by Churchill (1959) and subsequent authors (e.g. Seddon 1972).

In the nearshore submarine area north of Mandurah the mixed lag of shells and their ages indicate that estuarine conditions existed locally up to 3000 C14 yrs BP. The estuarine deposits would have been protected by a spit or barrier (similar to the modern Wonnerup Inlet, Geographe Bay). The barrier was probably flanked to seaward by a beach and bank facies. The entire sequence of estuary, barrier spit and bank sediments have since been eroded leaving a gravel lag of mixed estuarine, bank, beach and rocky pavement shells.

Palaeogeographic reconstructions

For convenience, the reconstruction of Holocene palaeo-geography is described in 5 stages (Fig. 11):

Stage 1: pre 8000 C14 yrs BP
Stage 2: 8000-6000 C14 yrs BP
Stage 3: 6000-4000 C14 yrs BP
Stage 4: 4000-2000 C14 yrs BP
Stage 5: 2000 C14 yrs BP to present

Stage 1:pre 8000 C14 yrs BP: During the last glaciation around 20000 yrs BP the limestone ridge-and-depression landscape between Mandurah and Fremantle was exposed with the sea situated approximately some 50 km to the west along the 100 m contour. The local terrain consisted of two major ridges standing some 40-60 m above the floor of an elongate valley which extended northward from the Peel-Harvey valley to open onto a flat plain near Fremantle. Apart from several low and discontinuous ridges, the valley was featureless. It is possible that at this time the Harvey, Murray and Serpentine rivers all discharged into the southern part of the valley before flowing northwards to coalesce with the Swan River near Fremantle. By about 18000 yrs BP the ice age ended and world sealevel started to rise. The sea first entered the valley around 8500 C14 yrs BP resulting in local deposition of estuarine deposits in the deeper depressions.

Stage 2:8000-6000 C14 yrs BP: Between the period 8000-6000 C14 yrs BP when sealevel rose to near its present level the ancestral elongate valley was flooded to a depth of some 20 m, to form a continuous waterway, the Warnbro-Cockburn Depression. The mainland shore, comprised of limestone rocky shores, pocket beaches and localised parabolic dunes, was situated along the western margin of the Spearwood Ridge. The Garden Island Ridge was mostly a continuous elongate island with only one major opening to the south. It is also probable that the Five-Fathom-Bank Ridge was almost totally inundated.

Marine erosion of the weakly lithified Garden Island Ridge resulted in a breach developing near Rockingham which allowed sediment supplied from the eroding breach and from the western side of the ridge to be transported into the depression behind. The transported sediment was confined to loci of wave convergence, which extended eastward, and a discrete east-west bank began to form. Concurrently, the mainland shore was subject to normal littoral processes which transported sand along the coast from the south. Where the mainland topography was low, sand was mobilised inland to form transgressive parabolic dunes perched on the Spearwood Ridge.

The majority of sediment impelled north by littoral drift, however, progressively accumulated under the combined effect of the shelter of the Garden Island Ridge and the influence of the now inundated lower limestone ridge to form a bank (the incipient Rockingham Bank) topped by a series of recurved spits. These spits eventually enclosed a northfacing embayment. While the embayment was open to the sea its southern part became filled with seagrass bank sediments that were in part covered subsequently by the spits. By 6500 C14 yrs BP the spits linked with the Spearwood Ridge in the north thereby isolating the embayment from the sea, the northern half remaining an unfilled water body some ?10 m deep.

In the Mandurah area a barrier spit-protected estuary developed at the mouth of the Peel-Harvey exchange channel. In response to the nett northerly littoral drift and the protection of Murray reefs and Halls Head, the estuarine-spit complex probably was oriented parallel to the coast extending from Mandurah toward the north.

Stage 3:6000-4000 C14 yrs BP: During this period breakdown of the Garden Island Ridge and partitioning of the Warnbro-Cockburn Depression into discrete basins continued. Sand transported onshore and alongshore contributed to the rapid growth of the Rockingham Bank and the subaerial beachridge plain, which by 4000 BP had extended halfway across the depression. Another major breach in the Garden Island Ridge was developed also during this period and sands were transported through the breach into the depression behind to initiate and contribute to the formation of the Becher Bank. By 4000 BP the Becher Bank had sufficient elevation to influence the shape of the shoreline behind.

The barrier spit-protected estuary was still located to the north of the Peel-Harvey estuary exchange channel.

Stage 4:4000 -2000 C14 yrs BP: During this period break-down of the Garden Island Ridge, growth of Becher Bank, and progradation of beachridge plains over the axes of both Becher and Rockingham banks continued. Sand transported onshore and alongshore contributed to growth of Becher Bank to the extent that the growth pattern of the entire Rockingham-Becher Plain began to re-

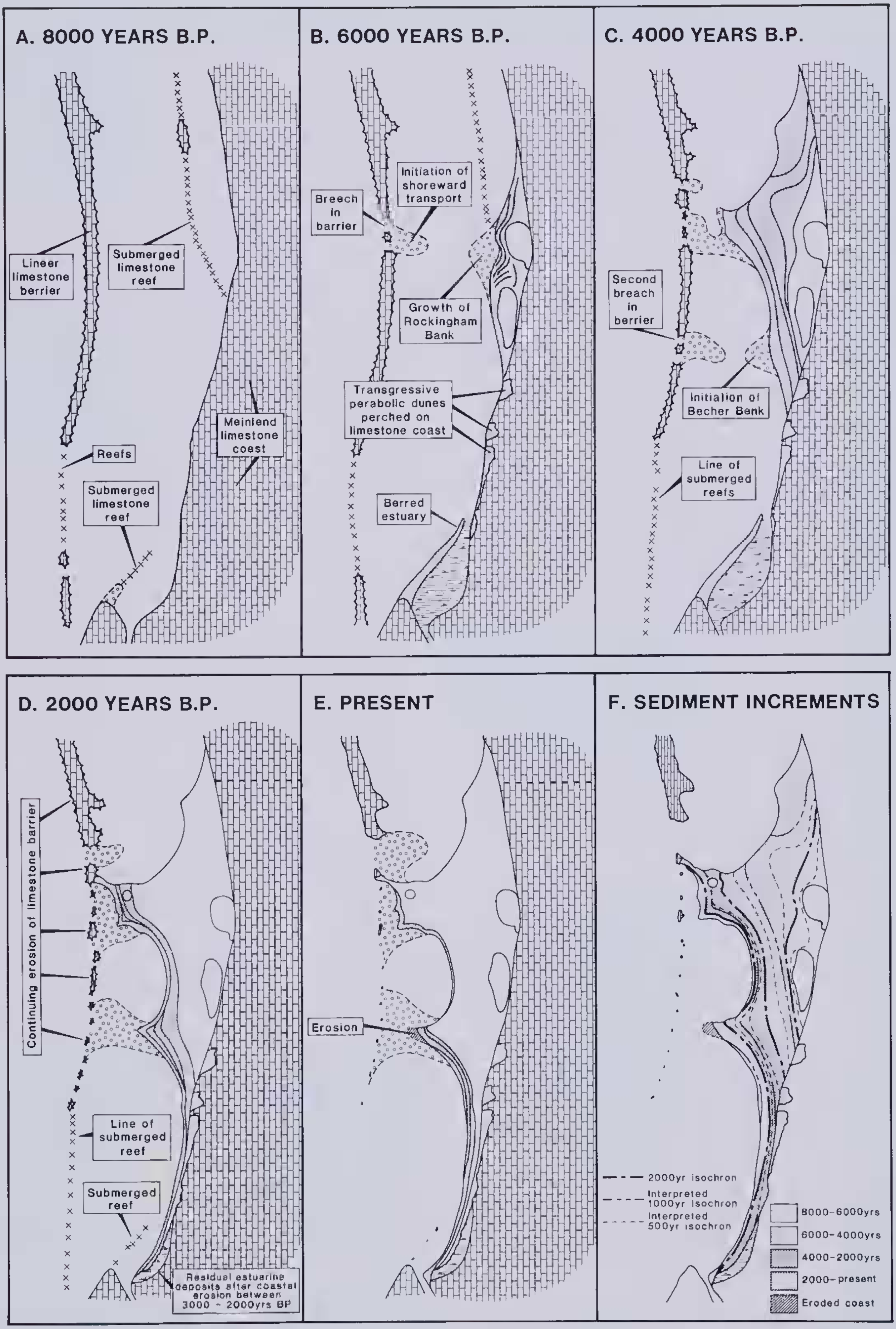

Figure 11 The geomorphic history and coastal changes in the study area over the past 8000 yrs in 2000-yr intervals; F shows the asymmetric incremental nature of sediment accretion.

flect the presence of both banks. The pattern of growth of the Rockingham Plain became complex as it neared the Garden Island Ridge, with smaller scale tombolos and spits developing behind the remnants of the ridge and the broken chain of submerged reefs to the west. By *c* 2 500 C14 yrs BP Rockingham Plain joined with the Garden Island Ridge linking Pt Peron with the mainland and effectively separating Warnbro Sound from Cockburn Sound. Subsequently, Lake Richmond was isolated from Cockburn Sound by the advancing Rockingham Point which linked with the older ridges to the west. Towards the end of this period Becher Bank had developed to the stage where rapid advance of the subaerial Becher plain was possible. This consumed most of the available sand arriving from the south, effectively depleting the supply to beaches to the north. Consequently while Becher Point prograded rapidly, the shores to the north remained static or prograded slowly.

Up to 3000 C14 yrs BP the barrier spit-protected estuary was still located to the north of the Peel-Harvey estuary exchange channel. Thereafter the entire barrier-estuary sequence was eroded to leave a ribbon-shaped shell gravel lag deposit to be buried later by nearshore shelf sand and onshore aeolian sand.

Stage 5:2000 C14 yrs BP to Present: During the last 2000 yrs breakdown of the Garden Island Ridge and growth of the Becher Plain has continued. The growth of the Becher Bank and plain combined to deplete the supply of sand to the beaches to the north. Consequently some beaches north of Warnbro Sound have undergone minor erosion whilst the shore of Warnbro Sound itself has advanced more slowly. The presence of truncated ridge trends south of Becher Point suggests that Becher Pt itself ceased advancing some time within the last 500 years with resulting erosion and realignment of the point. The final coastal configuration and geography as a result of the coastal evolution and the incremental sediment additions for each 2000 yr interval are shown in Fig. 11. The incremental sediment additions indicate that supply of sediment, to a large extent, has been from the south possibly from the eroding Leschenault-Preston Sector as suggested by Semeniuk & Meagher (1981).

Discussion

The natural history features of the Rockingham-Becher Plain are significant in Western Australia and also have worldwide importance for a number of reasons. Firstly, the Rockingham-Becher Plain comprises the largest accumulation of Holocene sand in the region of the inner Rottnest Shelf coast, with *c* 5 x 10^9 m^3 of sediment stored in system. In contrast, elsewhere in the region, the Leschenault-Preston Sector contains *c* 3 x 10^9 m^3 of sediment, and Geographe Bay contains *c* 0.5 x 10^9 m^3 of sediment. As a consequence of the large amount of stored sediment, the Holocene sand deposit of the Rockingham-Becher Plain potentially contains a wealth of natural history information. For instance, the Holocene deposits preserve an interesting stratigraphy and history of sedimentation.

The sedimentary system of the Rockingham-Becher Plain is relatively simple and can be classified as a carbonate complex, akin to the Shark Bay seagrass sedimentary complexes, notwithstanding that in the Rockingham-Becher area there also is a significant quartz content in the sediment. The stratigraphy of the area also is relatively simple, consisting essentially of three main units accumulated in superposition, and each representing a distinct environment of deposition. The style of sedimentation and the coastal history of the area, in that it is an example of Holocene sedimentation in a bathymetrically complex coastal zone, contrasts with that of the other sectors of the inner Rottnest Shelf (Searle & Semeniuk 1985) and, for that matter, areas such as Shark Bay (Logan & Cebulski 1970) or the tropical macrotidal coast of northwestern Australia (Semeniuk 1986b). Consequently, the Rockingham-Becher Plain area is significant in that the sedimentologic-stratigraphic model derived from this area provides a case book example of worldwide importance of Holocene sedimentation and stratigraphic evolution.

Additionally, a range of natural features in the area provide a unique opportunity to enable reconstruction of sealevel history and geomorphic evolution of the plain. These features include the abundance of Holocene and contemporary skeletal material available for radiocarbon dating in the carbonate-rich sediment, the specific sealevel indicators as preserved in the stratigraphic sequence, the microtidal setting, and the distinctive parallel beachridge coastal geomorphology that results from shoreline progradation. In contrast to many other sedimentologic settings elsewhere in the world, the microtidal setting and facies types of the Rockingham-Becher area has resulted in a simple and concise layered stratigraphy. Again, in contrast to other sequences elsewhere, the abundant shell material in the Rockingham-Becher deposits enables shells of various phylogenetic groups to be rigorously selected for radiocarbon analysis, and allows for dating from a selected stratigraphic interval. Other sequences elsewhere in the world or in eastern and southern Australia, while they may exhibit distinct beachridge trends do not necessarily contain abundant shells for radiocarbon processing; those that are composed of abundant shells and carbonate sediment do not necessarily exhibit the definitive and extensive coastal beachridge patterns or depositional environments present in this area. The factors of abundant shell material available for C14 analysis, the simple stratigraphy, and the definitive geomorphic trends are all present *in conjunction* in this study area.

Another important feature is that beachridge plains described worldwide frequently contain a sequence of ridges that reflect changes in depositional style during the period 7000 yrs BP to present. The Rockingham-Becher Plain on the other hand reflects a consistent depositional style throughout the latter period of the Holocene. As a consequence the geomorphology and stratigraphy of the Rockingham-Becher Plain assumes a national to worldwide significance, and it is suggested here that the area can be used as a model for coastal evolution for global geomorphic, sedimentologic and stratigraphic studies.

In addition, because it records a depositional history from 7000 C14 yrs to the present, and contains a preserved stratigraphy and geomorphology throughout this interval of the Holocene, the Rockingham-Becher Plain also assumes importance as a potential resource to investigate long term climate changes and cyclic sedimentation patterns. This has important implications for climatologists attempting to unravel Holocene climate changes over the past 7000 yrs as an index to predicting future climatic trends.

The record of sealevel history preserved in the sequences of the Rockingham-Becher Plain also is important. The Western Australian coast always has been the focus for global interest in sealevel studies because of the pioneering studies of Fairbridge (1961) centred on Rottnest Island and Point Peron. Although the accretionary sedimentary record provides evidence on sealevel history that differs with that derived from rocky shores, the record preserved in the stratigraphy under the beachridge plains is still of global importance. This sealevel history that has been documented as a standard example of sealevel response for this part of the continent and, in conjunction with the evidence from elsewhere in southwestern Australia, provides an important addition to a global to regional understanding of Holocene sealevel history.

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